Fermilab

SDC SOLENOID DESIGN NOTE #173

TITLE: Power Supply for SDC Solenoid

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I saw this article, "Power Supply Design for Superconducting Magnet Applications", by McCarthy and Smith, in the Spring, 1992 issue of **Superconductor Industry**. One of the authors, Jack McCarthy, was an electrical engineer in the Fermilab Accelerator Division for 20 years.

POWER SUPPLY DESIGN FOR SUPERCONDUCTING MAGNET APPLICATIONS

Superconducting magnets have some unique requirements that call for novel design configurations.

by Jack McCarthy and Christopher C. Smith

Superconducting magnet power supplies have some unique demands placed on them. Many of today's larger projects require power systems that can supply many thousands of amperes of current at precision on the order of 5 ppm or better. While it is relatively simple to design and produce such power supplies in the few kilowatt range, it is quite another matter when the required powers approach, and many times exceed, megawatt levels.

One of the most persistent problems associated with designing high current power supplies is determining reasonable and realistic system specifications. Occasionally power supplies have much tighter specifications than are actually required for the application in which they will be used. This is often due to the fact that there are many interpretations of the terms typically used to specify the design and operational parameters of magnet power supplies. Therefore, a brief review of the most common terms is in order (these definitions are from the Third Edition of the IEEE Standard Dictionary of Electrical and Electronic Terms).

Line Regulation: The maximum steady-state amount that the output voltage or current will change as a result of a specified change in input line voltage. Regulation is given either a percentage of the output voltage or current, or as an absolute change ΔE or ΔI.

Warm-Up: The time (after power turn on) required for the output voltage or current to reach an equilibrium value within the stability specification.

Stability (Drift): The change in output voltage or current as a function of time, at constant line voltage, load, and ambient temperature.

Common Mode Noise: The noise voltage which appears equally and in phase from each signal connected to ground.

Temperature Coefficient: The percent change in the output voltage or current as a result of a 1 degree-Celsius change in the ambient operating temperature (percent per degree Celsius).

Linearity: The correspondence between incremental changes in the input signal (resistance, voltage or current) and the consequent incremental changes in power supply output.

Slewing Rate: A measure of the programming speed or current-regulator-response timing. The slewing rate measures the maximum rate-of-change of voltage across the output terminals of a power supply. Slewing rate is normally expressed in volts per second ($\Delta E/\Delta T$) and can be converted to a sinusoidal frequency-amplitude product by the equation $f(E_{pp})$= slewing rate/π, where E_{pp} is the peak-to-peak sinusoidal volts. Slewing rate = $\pi f(E_{pp})$.

Ripple Voltage or Current : The alternating component whose instantaneous values are the difference between the average and instantaneous values of a pulsating unidirectional voltage or current.

Regulation: The maximum amount that the output will change as a result of the specified change in line voltage, output load, temperature or time.

Dynamic Deviation: The difference

between the ideal value and the actual value of a specified variable when the reference input is changing at a specified constant rate and all other transients have expired.

Absolute Envelope of Uncertainty: The determination of which parameters are important for a specific application, and the maximum error associated with those parameters.

Once these parameters, their affect on the output of the power supply, and how they correspond to the operation of the magnet are thoroughly understood, a set of specifications can be written that will allow a power supply to be designed and constructed. More importantly, a good set of specifications describes a system that will work in the manner desired.

Design Specifications

After the output specifications have been determined, the design configuration of the power supply can be finalized. Smaller power supplies, on the order of a few kilowatts, are typically used for beam correction magnets. Many times these power supplies are of the transistorized, switch mode design, being relatively small, lightweight, and easy to construct. But for magnets that require thousands of amperes of current at tens of volts, such as dipoles and focusing quadrapoles, the switcher design is not usually effective due to the large number of semiconductor devices required, and the associated reliability and cost ramifications.

For larger power requirements, phase control thyristor configurations are the design of choice. Thyristors are now manufactured large enough, and reliable enough, to be used in magnet power supplies where precision and stability are of paramount importance.

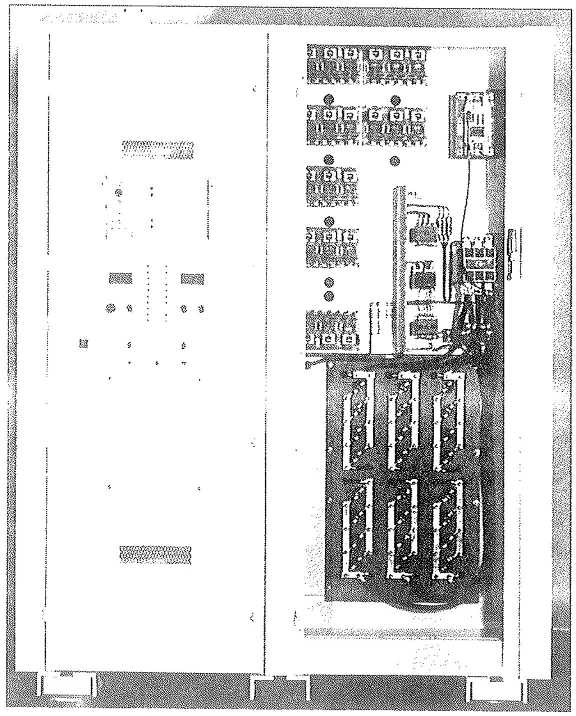

Photo 2. *± 12 volt, 10,000 amp Superconducting Super Collider Laboratory power supply.*

Superconducting magnet power supplies have a number of special requirements. Some are common to other types of power supplies, and others are unique to the superconducting application. Characteristics common to other power supplies include the need for bipolar current operation, low output ripple, and precision current measurement. Unique requirements center around the need for full current output at near zero output voltage levels, regenerative energy capabilities, and systems protection in the event of uncontrolled superconducting magnet quenching.

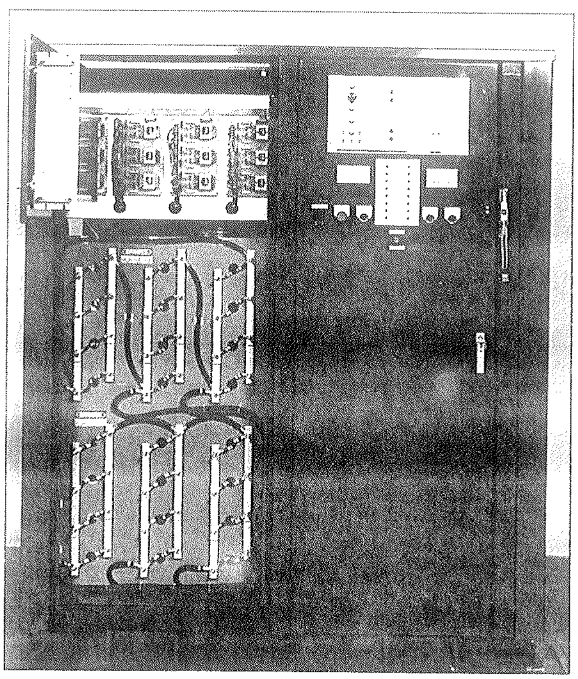

Photo 1. *± 40 volt, 8,000 amp Superconducting Super Collider Laboratory power supply.*

Power supplies for superconducting magnets are generally low voltage, high current systems. For example, the power supplies ordered from Dynapower for the SSCL so far include: 6 volts, 15,000 amps; ±40 volts, 8,000 amps (See photo 1); and ±12 volts, ±10,000 amps (See photo 2). Superconducting magnet loads exhibit high inductance and minimal resistance, leading to a long time constant (L/R). This long time constant, on the order of 500 seconds, dictates special feedback circuits that allow the power supply to adequately control the current to the magnet. In addition, due to this long time constant, power supplies such as those for the SSCL are very susceptible to line related reference noise. Therefore, they require highly noise immune input circuitry or on-board DAC'S.

As can be seen, some of the above-mentioned power supplies are single quadrant (I), some are two quadrant (I, III), while others are capable of operating in all four quadrants (see Fig. 1). This is of great importance with superconducting magnet power systems as many times the power supply must discharge the magnet as well as charge it (i.e. energy will flow in both directions between the power supply and magnet). The power supply must be carefully designed so that all operational portions of the system can accommodate the reverse voltage. For example, in the output ripple filtering, the capacitors must be capable of bipolar voltage operation, and in some cases current measuring devices must be able to determine not only the magnitude of the current but also the direction of current flow.

A very unique demand placed on superconducting magnet power supplies is that they must be capable of providing full rated current at close to zero output voltage. When a magnet is operated in the superconducting region, the resistance of the magnet is virtually zero, therefore the voltage drop across the magnet is also close to zero when the current is not changing. This particular requirement necessitates extremely careful magnetics design to ensure that the currents through the interface transformers, which are used to parallel various wye groups, are properly balanced. The fact that superconducting magnets can operate at full current at many different voltages requires that transformers be matched independently for both open circuit output voltage and impedance.

Also, interphase transformers must be increased in cross sectional area to insure, for instance, that they force 120° conduction (in a double wye with interphase connection configuration) at full current and zero voltage, where the volt second integral across the interphase is significantly higher.

Quench Detection

Another aspect of superconducting magnet power supplies is the requirement for low output voltage ripple. Low ripple is necessary for proper quench detection to occur. Quenching is when a portion of the superconducting magnet makes the transition from the superconducting to the normal mode. In the superconducting mode, a magnet is capable of passing tremendous amounts of current with virtually no losses. The magnet resistance is so low that there are no heat losses in the coils. If the magnet quenches, the resistance of the coils increases dramatically and the high currents could cause destruction of the magnets from heat overload.

The quenching circuits for single magnets typically monitor the difference between the rate of change of current times the magnet inductance, which is generated electronically, and the voltage across the magnet coil. As long as the magnet remains superconducting, $V_{coil} \approx Ldi/dt$ to a good approximation. However, when a coil quenches $V_{coil} = Ldi/dt + R(t)i$, where R(t) is the time dependent resistance caused by the three dimensional spread of the quench.

For magnets which are not stable (low copper to superconductor ratio), a quench can be quite destructive. If left to develop normally, all of the stored energy of the magnet is dissipated in the small volume of the quenched magnet. Depending on the design of the magnet, this can be totally acceptable, however, most designs employ either an external dump resistor to dissipate the stored energy or a heater circuit to quench a large volume of the magnet and thus reduce the maximum temperature rise of any piece of conductor. The external resistor has the virtue of directly removing energy, thus reducing refrigeration loads. When the current flows through the dump resistor, high voltages are generated across the resistance due to the large currents in the magnets. The power supply must be capable of being subjected to these common mode voltages without suffering damage. A well designed and constructed systems will have hi-pot specifications of 5,000 volts or better.

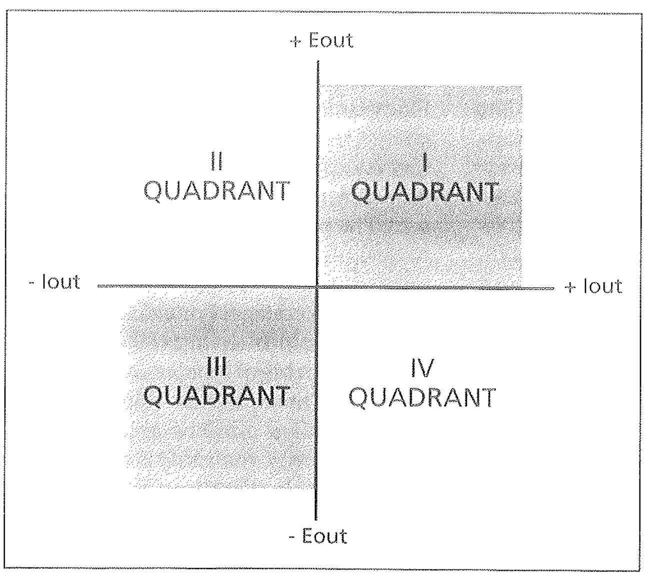

Fig. 1: *The four operating quadrants of a magnet power supply.*

The sooner a quench is detected the less likely it is to damage the magnet. Early quench detection will allow removal of the power supply quickly to reduce additional energy added by the power supply and quicken firing of the quench protection devices. The result of all of this is to reduce the total amp^{2}sec, integral which is a measure of the maximum temperature of the initial quench point.

Superconducting magnet power supplies must incorporate systems for protecting the power supply from the stored energy in the magnets in the event of a power failure. High current superconducting magnet power supplies are generally designed using thyristors as the rectification and regulation devices. A thyristor is basically a diode that has a terminal, called a gate, where a signal is applied to cause it to conduct current. Once the gate signal has been applied, and current is flowing, the only way to stop the current flow is to remove the current or cause it to reverse direction. There are a series of banks of thyristors in a typical power supply, and the current supplied to the magnet is cycled between these banks such that no one bank provides more than a fraction of the power. There is always one bank, however, that is turned on and powering the magnet. A typical six phase, wye primary star secondary power supply is shown in Fig. 2. In this case, each semiconductor bank carries one sixth the total output current.

If the main power is lost, the current flowing in the magnet will attempt to continue to flow through the last thyristors that happened to be operating at the time of power loss. It is easy to imagine what would happen to the semiconductors when three to twelve times their normal average current was applied. The minimum would be destruction of the semiconductors, with a distinct possibility of damage to the main power transformer and perhaps the superconducting magnet itself.

Therefore, a system to safely dissipate the current must be provided. In single quadrant power supplies, this is usually a free wheeling diode, capable of handling the full current, placed across the output. In normal operation (i.e., the power supply is powering the magnet), the diode is reverse biased and no current flows through it. If the power is lost, the magnet becomes the source, with polarity reversed and forward biases the diode, providing a safe path for the current to flow.

In two or four quadrant power supply a bank of bypass thyristors, capable of handling the full current of the power supply, must be used. This bank must be equipped with its own power source, typically a capacitive stored energy or battery backup UPS, that will activate the bypass in the event of a main power failure. The bypass system will then provide a path for the magnet current to flow that will not cause damage to the power supply or magnet.

One other aspect of superconducting magnet power supplies is that they require a soft start capability. In other words, when the main power is applied to the power supply, the output must ramp up gradually to the desired level. An instantaneous increase from zero to full output could cause false triggering of the quench protection system.

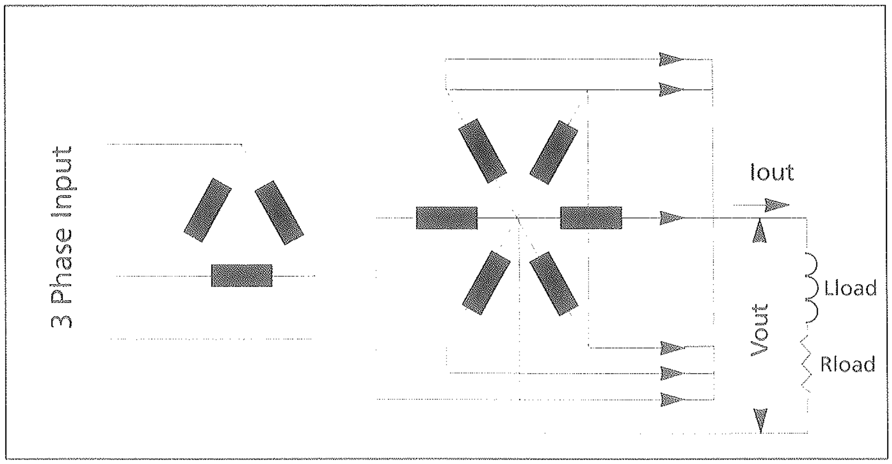

Fig. 2: *A six phase, wye primary, star secondary power supply main power and rectification section.*

Power supplies for superconducting magnets require sophisticated interlocking schemes in order to protect the magnets, the power supplies, and personnel. Interlocks consist of detection systems for magnet cryogenics, extreme voltage and current excursions, and major faults in control systems. Interlocks and controls are so sophisticated that a discussion of them would require a separate article.

10,000 Power Supplies

In addition to all of the above special requirements, a superconducting magnet power supply must also have superior reliability. An application such as the SSCL requires a large number, on the order of 10,000, of both normal and superconducting magnet power supplies for the LEB, MEB, HEB, and collider rings. It is imperative that these power supplies operate efficiently and reliably, as a failure can cause the particle beam to become unusable or be lost altogether. If that happens, experiments may be damaged.

The capability to accurately measure the current provided by the power supply is extremely important. In many cases, a simple resistive shunt is satisfactory. These devices are situated in one of the output legs, and are typically accurate to within ±0.25%. Shunts are relatively inexpensive, but have a number of disadvantages. One is that they offer no isolation from the output to the control circuitry. Another is that they generate heat losses due to their resistive nature. This is especially important at higher current levels.

Fortunately, there are a number of alternatives to resistive shunts. These include Hall effect devices and zero flux current transductors. These types of devices provide isolation in that they are not placed directly in line with the output. Rather, they are situated around the output bus, and are magnetically coupled. This configuration provides very good isolation and does not generate any losses. Additionally, devices such as the Dynapower Zero Flux Current Transductor are capable of meeting extremely stringent current measurement requirements, such as the ±2 ppm of the SSCL power supply shown in Fig. 2.

The topic of current measurement is highly complex, exceeding the scope of this article. For a paper that discusses different current measurement techniques, contact Dynapower and request Publication 110, "Survey of DC Current Measurement Techniques for High Current Precision Power Supplies."

As can be seen from this discussion, power supplies for superconducting magnets demand precision, careful design, ruggedness, and high levels of safety. While these things are important in any power supply, they are of critical importance for power supplies used to energize normal and superconducting magnets.

John D. McCarthy, technical director at Dynapower, graduated from the University of Illinois in 1969 with a B.S.E.E., at which time he joined Fermi National Accelerator Laboratory. He received his M.S.E.E. from Midwest College of Engineering in 1975. From 1976 to 1980 he served as deputy group leader at Fermilab. From 1980 to 1985, McCarthy was group leader of Power Supplies and Instrumentation for their Antiproton Source Department. In 1986 he became group leader for the Instrumentation Accelerator Division, and in 1988, department head, injector. During his twenty years at Fermilab, he was involved in all aspects of accelerator design, theory and commissioning. His accelerator experience has provided him with direct working knowledge of all types of power supplies. Since joining Dynapower in 1989, Mr. McCarthy has been involved in upgrading the circuitry for high precision and specialty power supplies. He was instrumental in the creation of the Dynapower dual phase locked loop firing circuit which is now a standard for high precision power supplies. He is currently spearheading the new advances in the line of switching power supplies under development at Dynapower.

Christopher C. Smith, marketing manager for Dynapower, holds a B.S.E.E. from Florida Technological University (now the University of Central Florida). Prior to joining Dynapower, Smith was product manager for an international manufacturer of semiconductor photolithography equipment. His duties at Dynapower include investigation of new markets, advertising and public relations, and international sales and marketing.